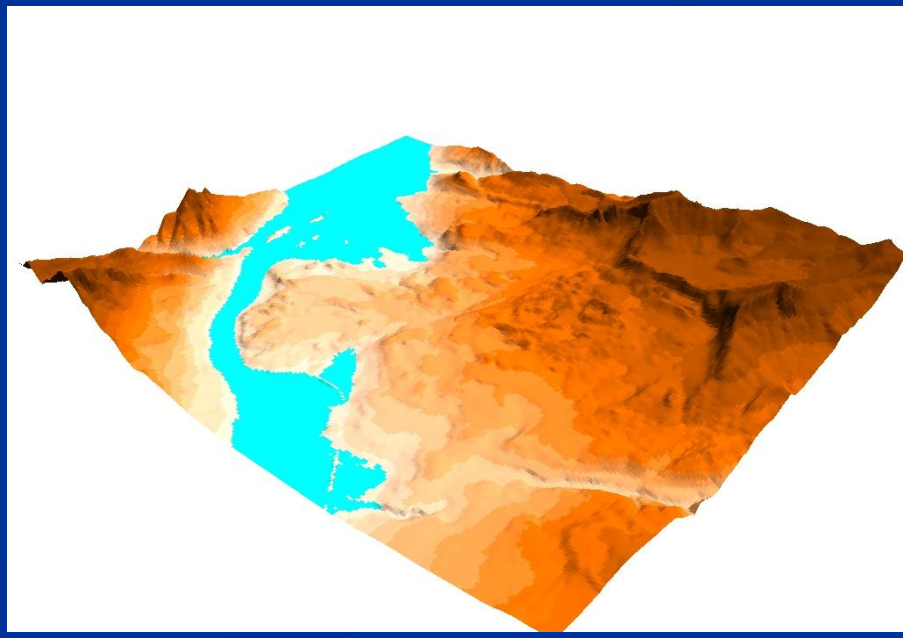
Cascadia: Earthquakes, Dams & Resilience

NW Hydro Operators Forum
May 7, 2013 Belluvue WA
Yumei Wang, PE, DOGAMI

Topics

- Earthquakes in PNW
- Seismic Risk to Dams
- Dam Examples
- Summary Remarks

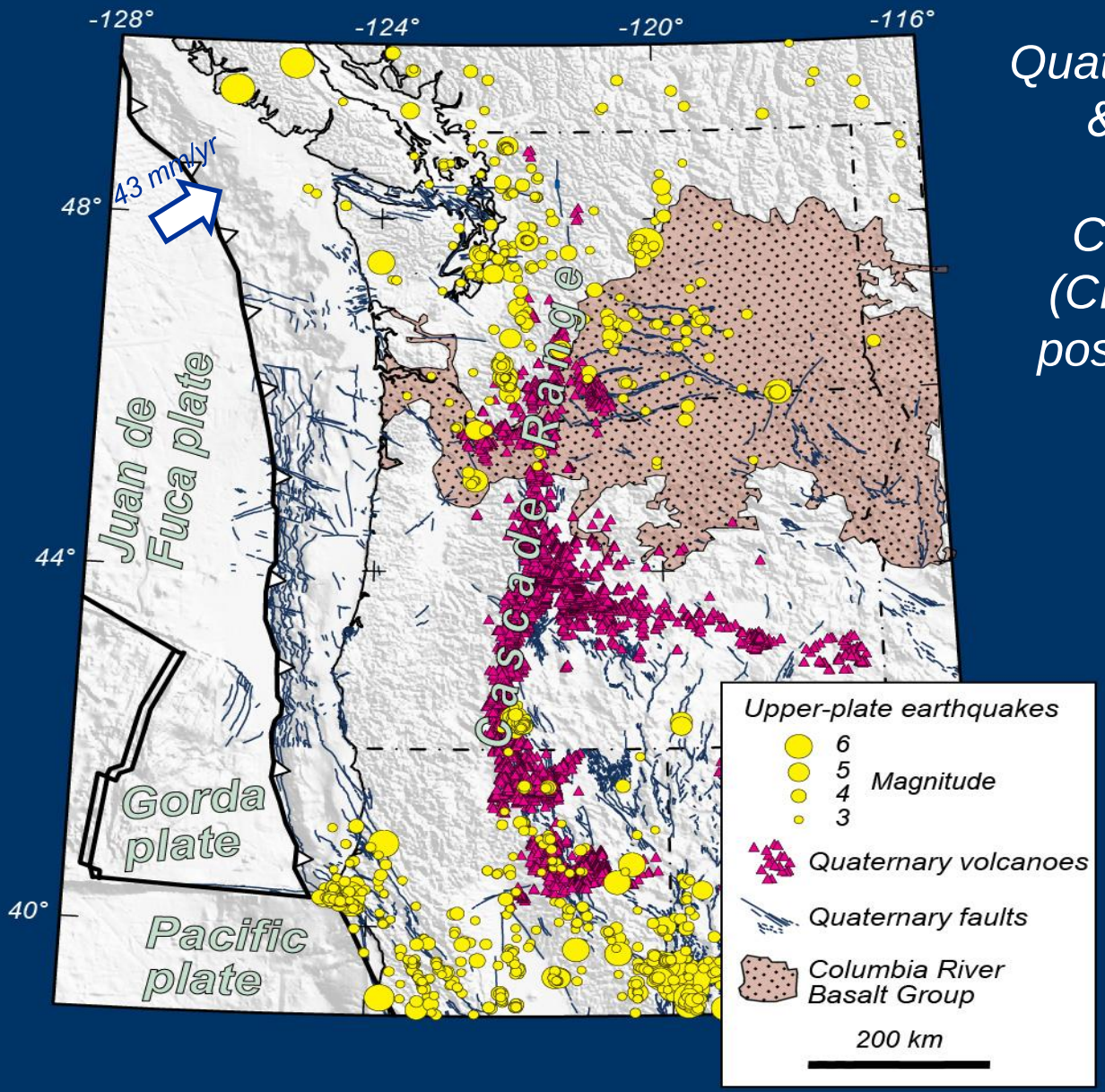
Bonneville Dam Looking U/S



Looking D/S

Earthquakes… strike without warning

PNW Faults & Earthquakes



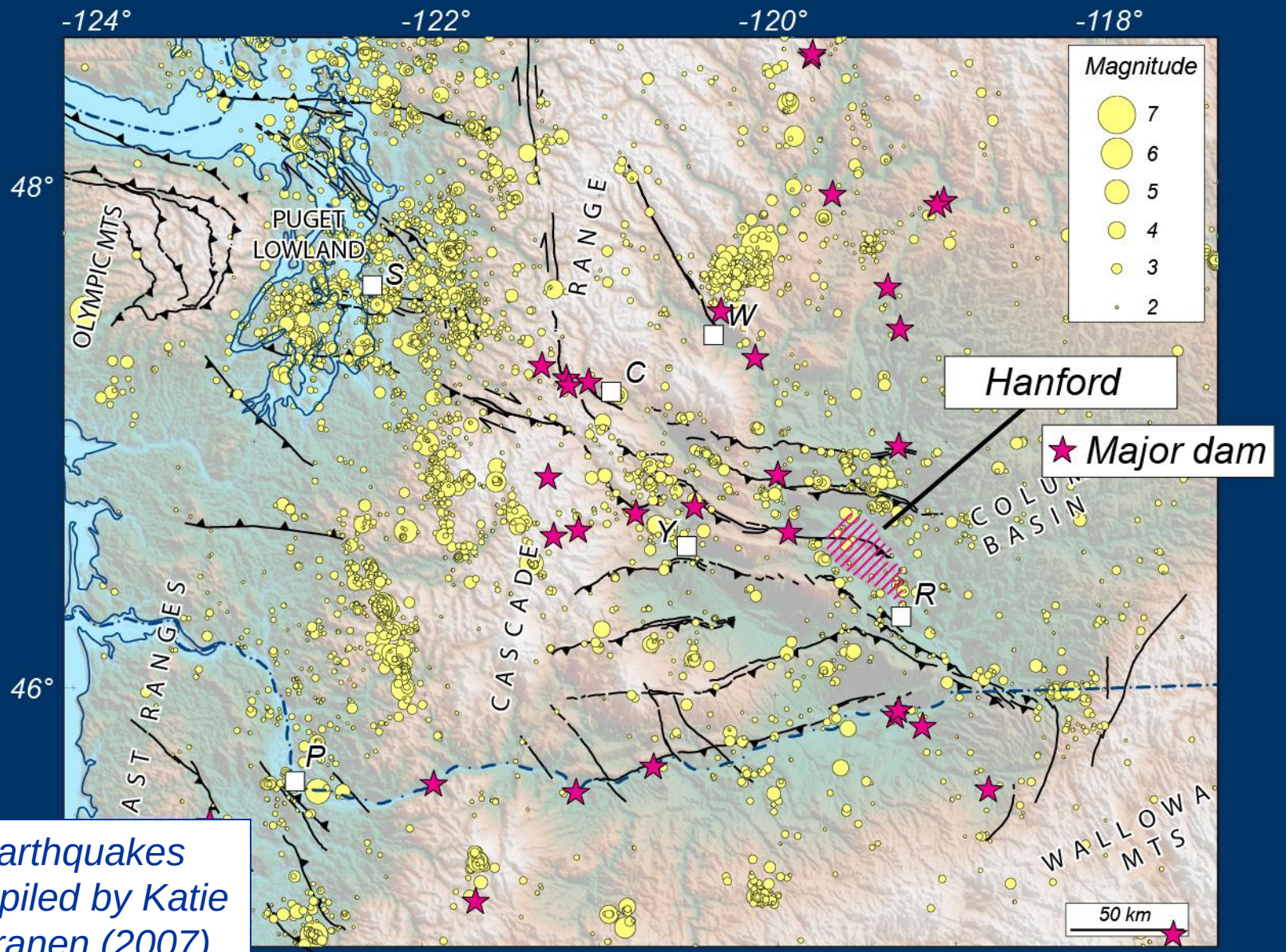
Quaternary faults, volcanoes, & earthquakes ($M \geq 3$)

Columbia River Basalts (CRB): strain markers for post-Miocene deformation.

R. Blakely, USGS

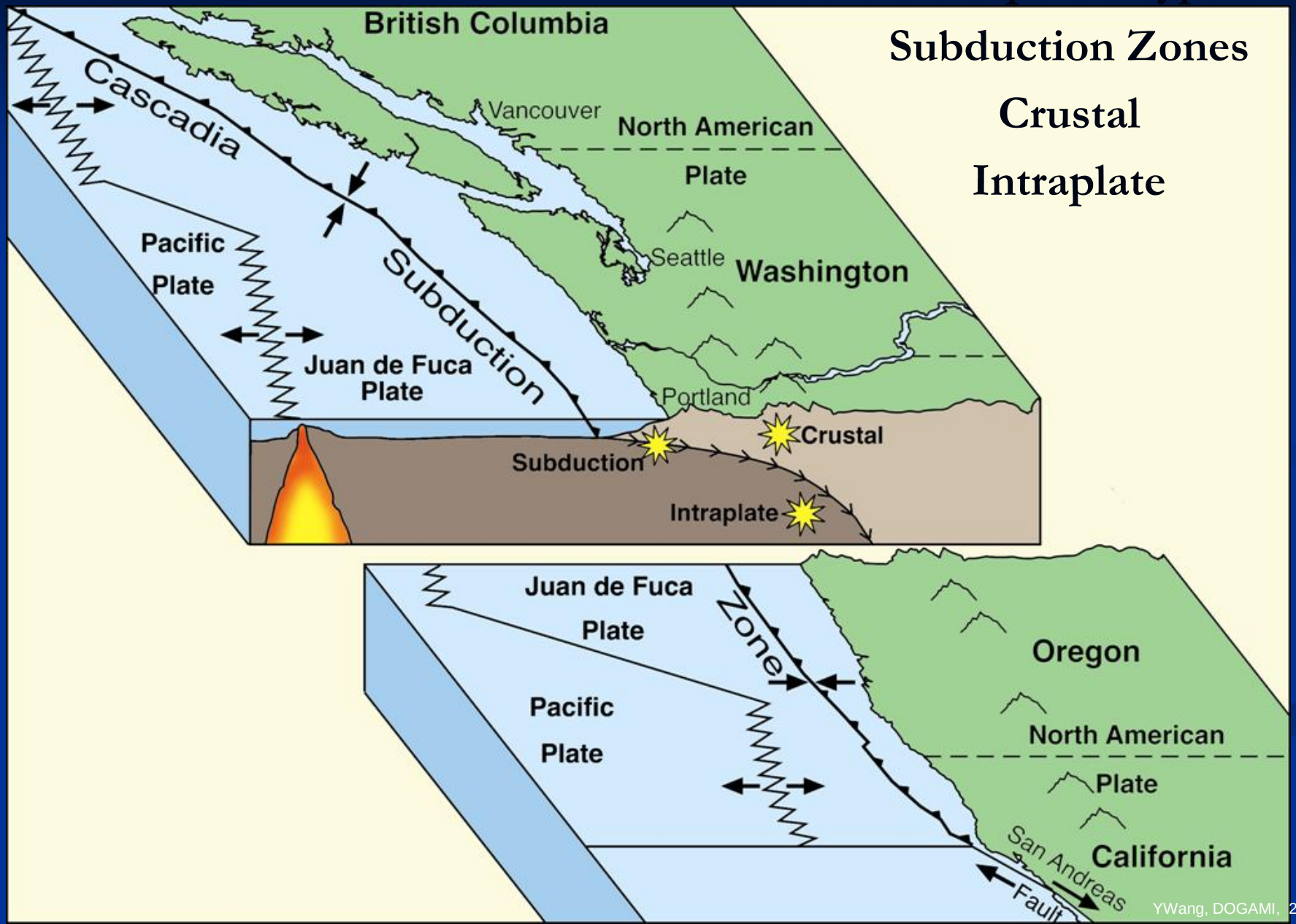
Recent Earthquakes & Dams

R. Blakely, USGS



Earthquakes compiled by Katie Keranen (2007)

Earthquake Sources



Probabilistic Ground Shaking Map

Source: USGS

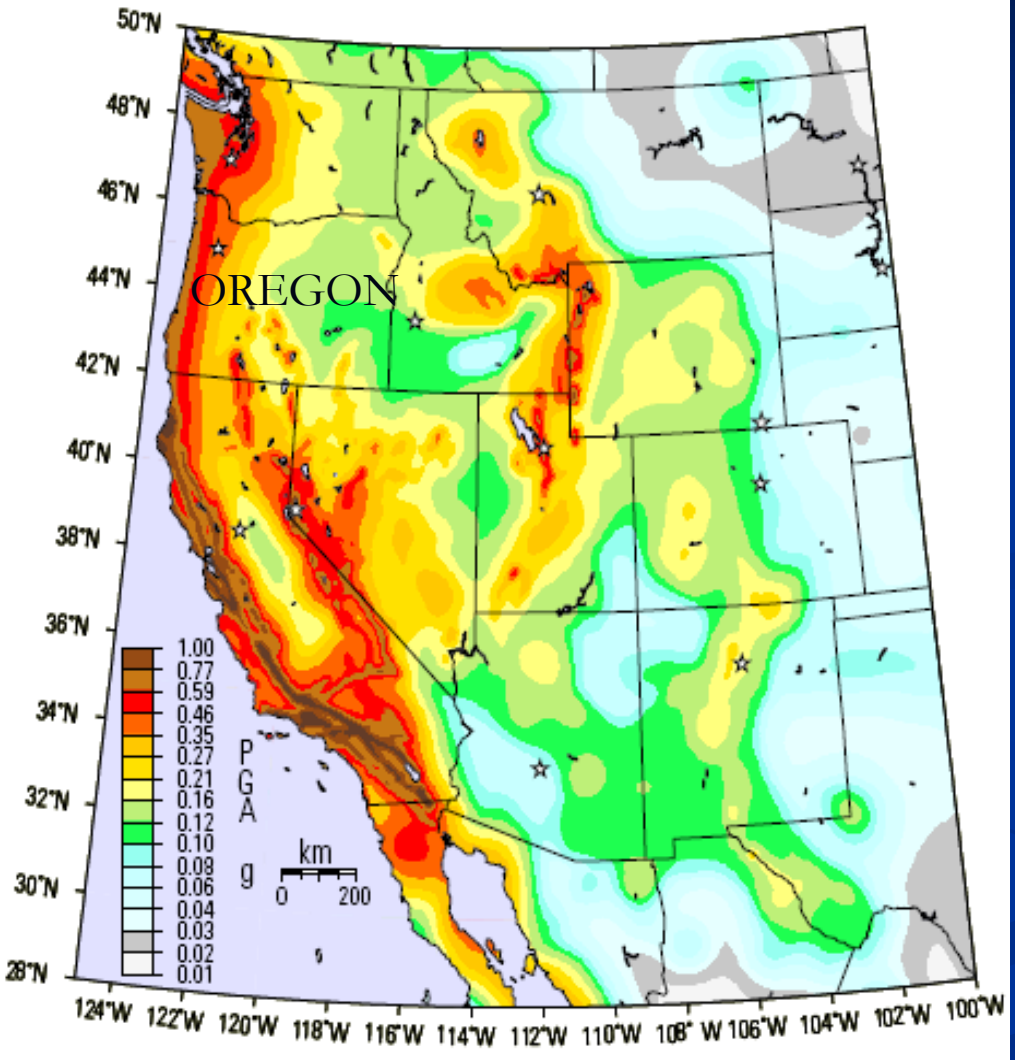


Figure 36. Map of 5-hertz spectral acceleration (SA) for 2-percent probability of exceedance in 50 years in the Western United States in standard gravity (g).

Cascadia Fault (subduction zone)

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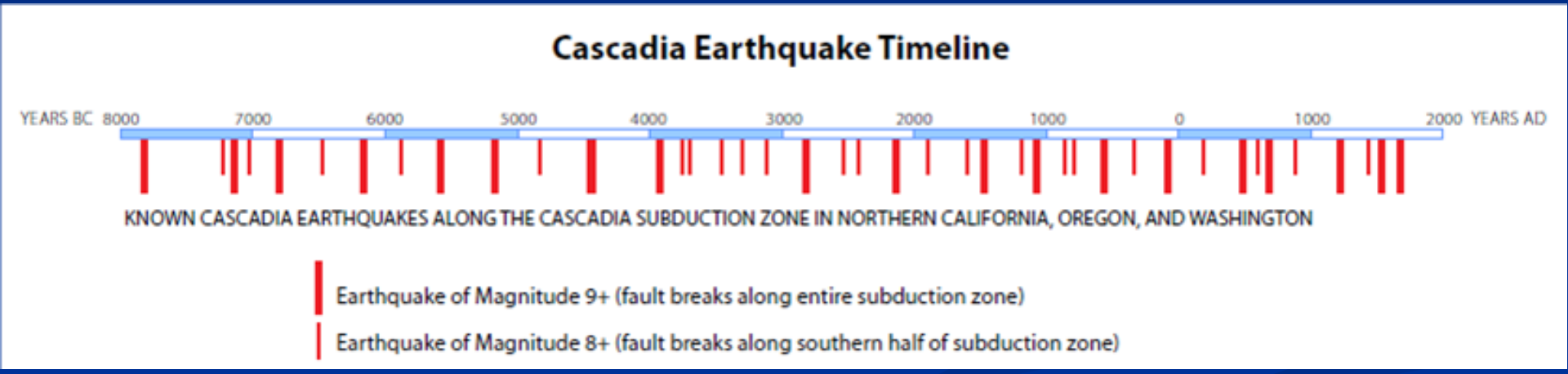
When, where, how big?

100%, don't know exactly when…

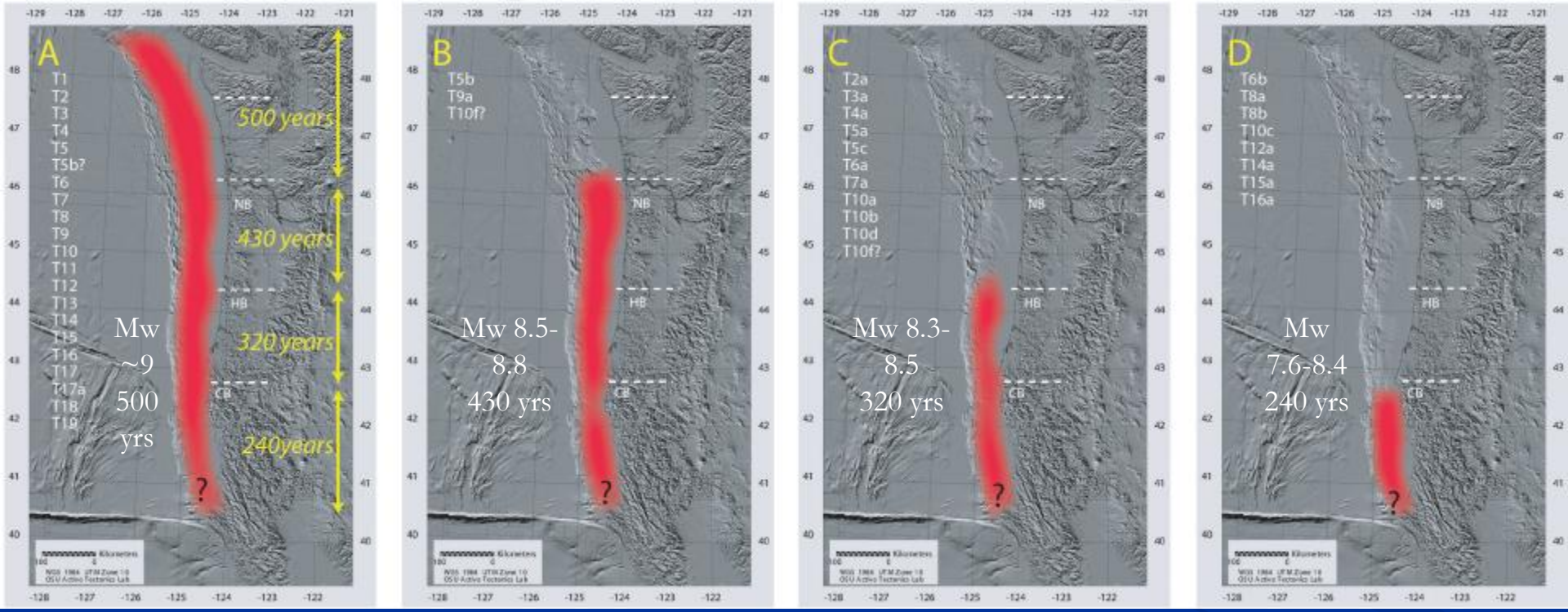


**(Goldfinger et al, 2012;
Image: DOGAMI Cascadia, 2010)**

- Many quakes in 10,000 yr geologic record
- ~M9 Jan 26, 1700 (313 yrs ago)

When, where, how big?…

Could be magnitude 8, or magnitude 9.2

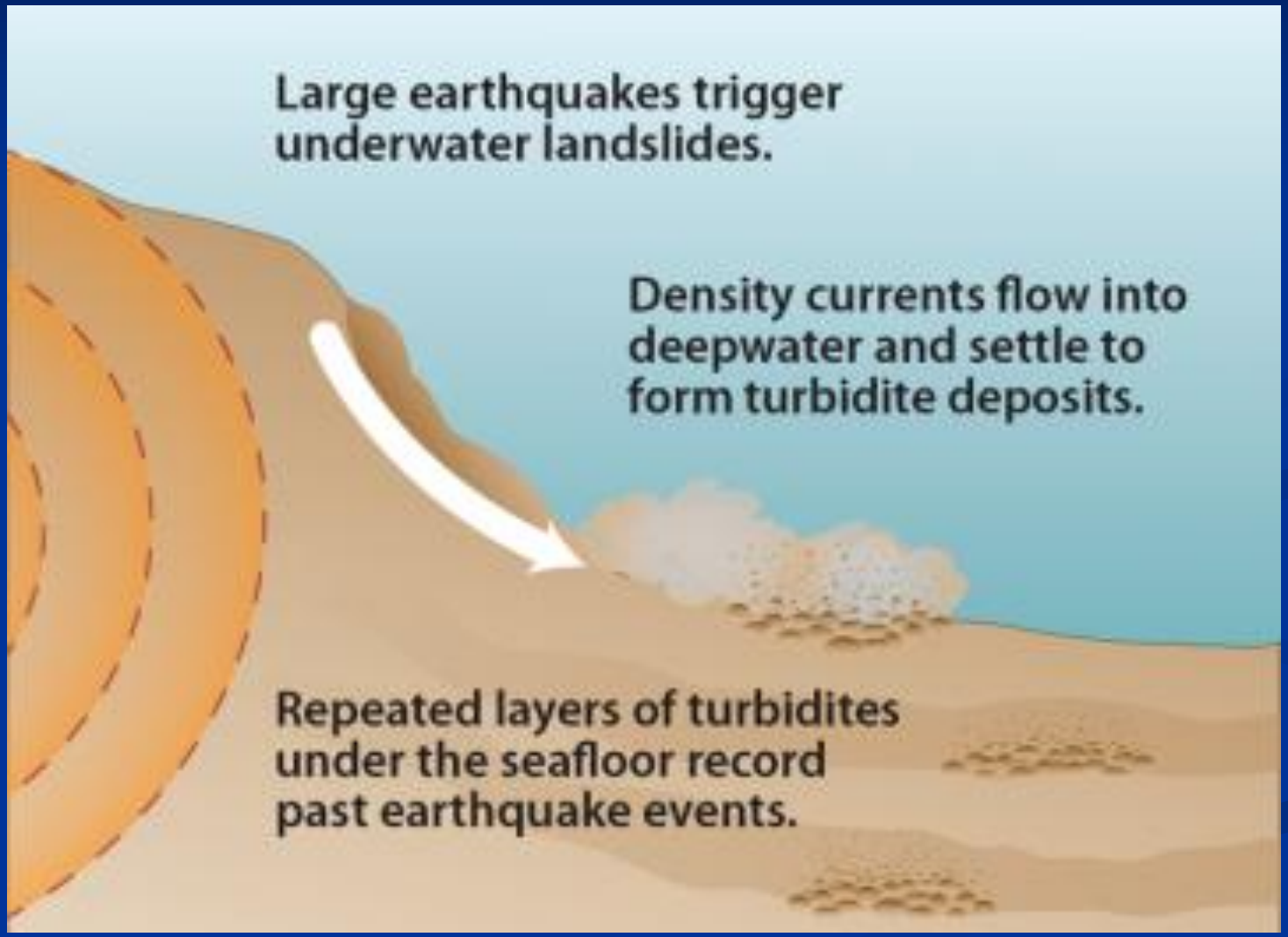


(Goldfinger et al., 2012)

- ~20 full length ruptures
- ~20 partial length ruptures. South most activity.

YWang, DOGAMI, 2013

Undersea Landslides: Turbidites



Credit: K Cantner, American Geological Institute

Strong Shaking & Damage in Western OR & WA

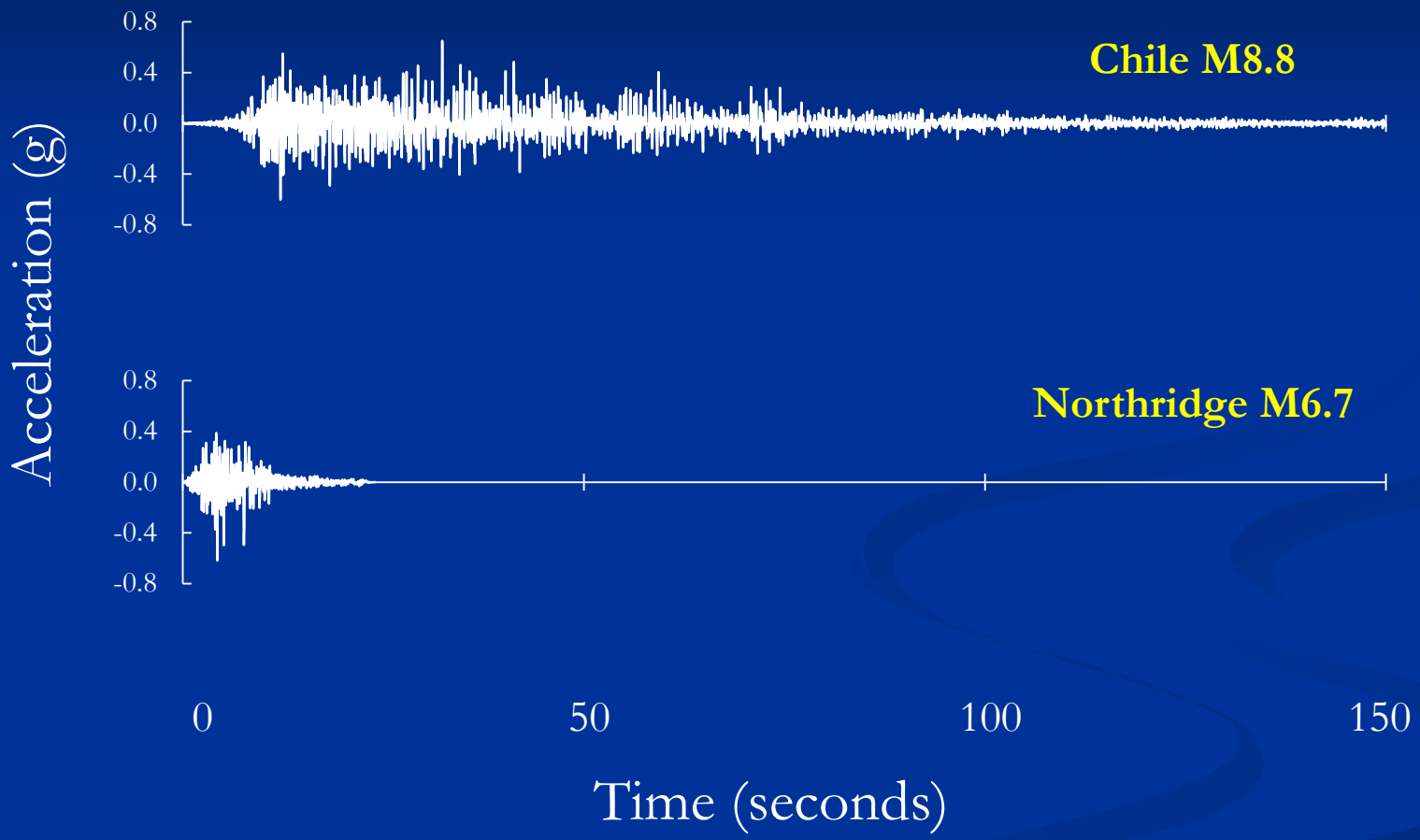
- Extreme Damage by Tsunami
- Major Damage in Coastal Areas
- Significant Damage in Valley

Levels & Duration
of engineering significance
vs
Perceivable shaking

DHS 2011 Analytical Baseline Study

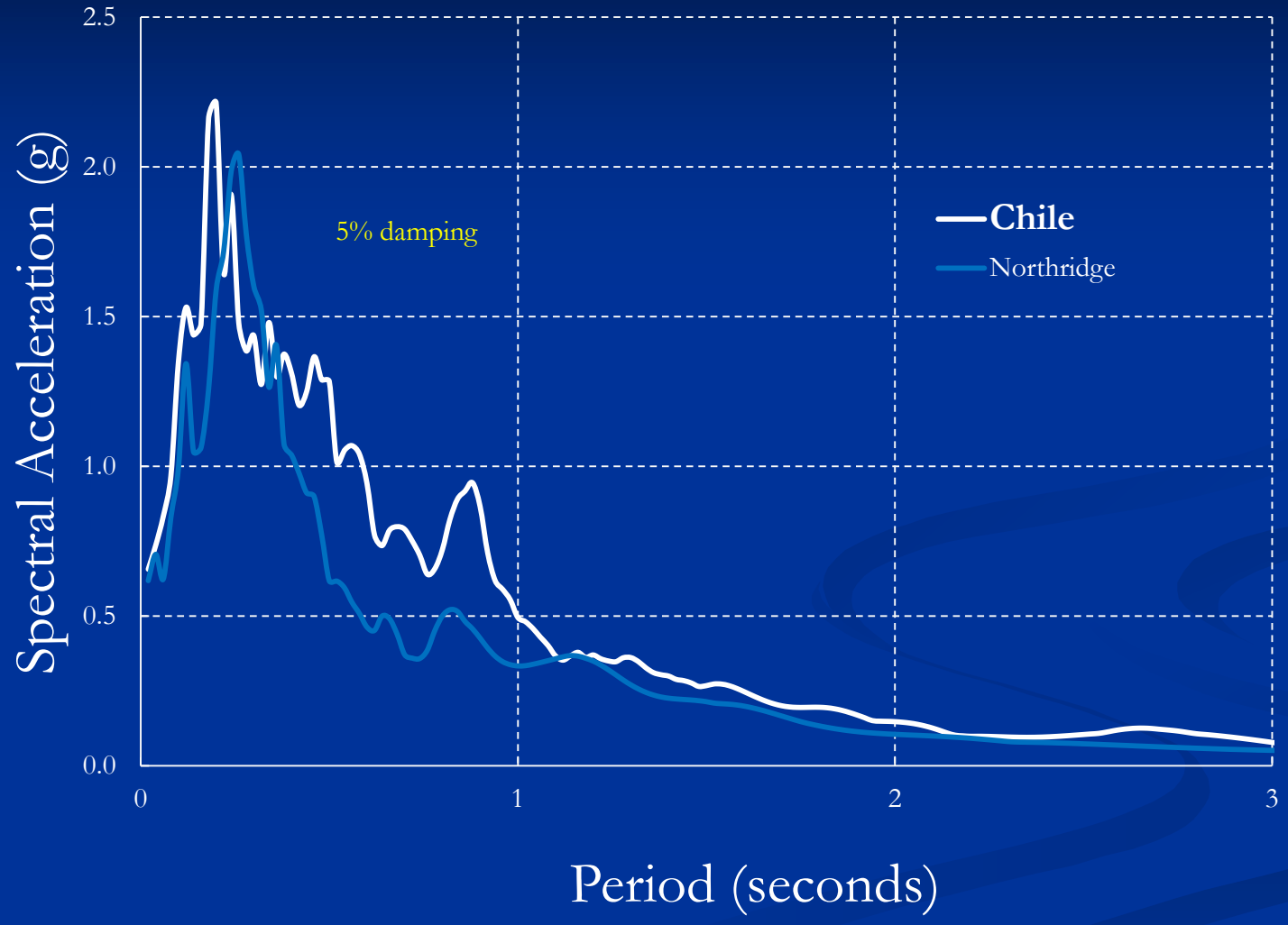
Duration: Chile vs Northridge

Source: D. Baska, Terracon



Response Spectra

Source: D. Baska, Terracon

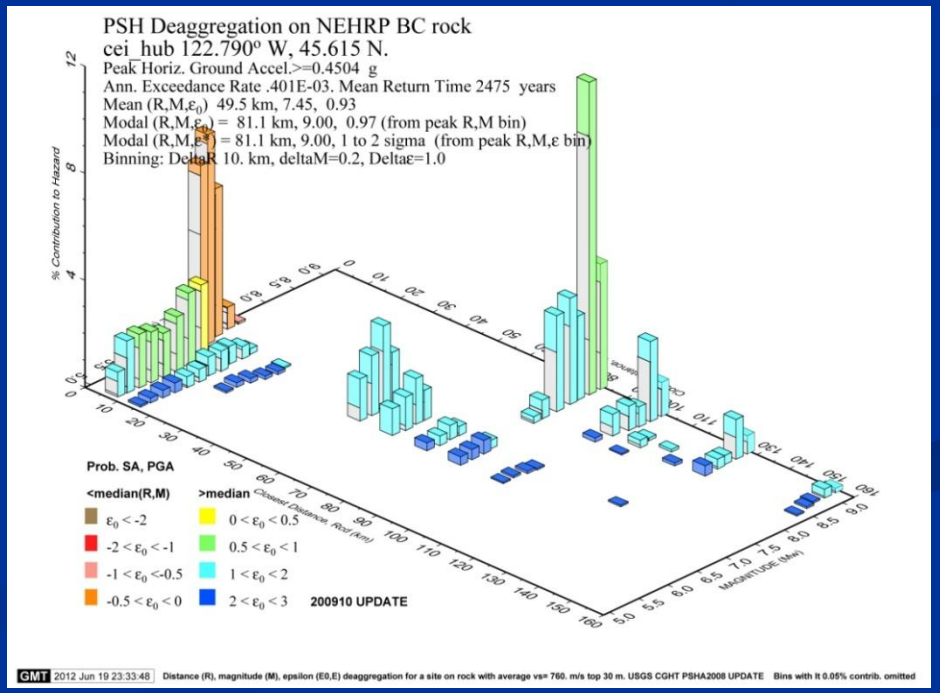


Cascadia Probabilities

- 10-40% Magnitude 8 or greater in next 50 yrs

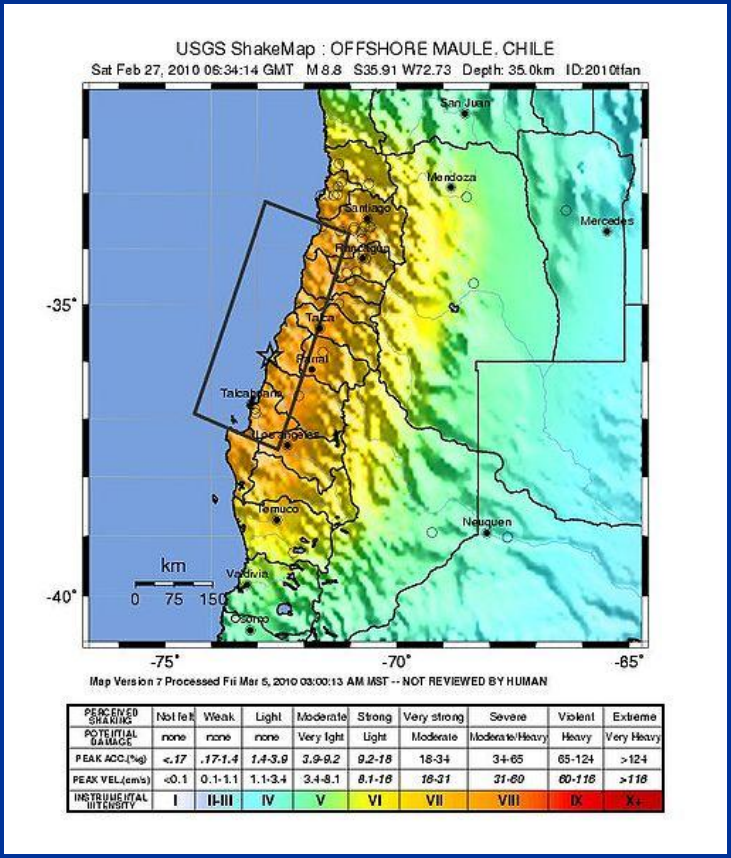
- USGS web tools: de-aggregate sources

  http://earthquake.usgs.gov/hazards/designmaps



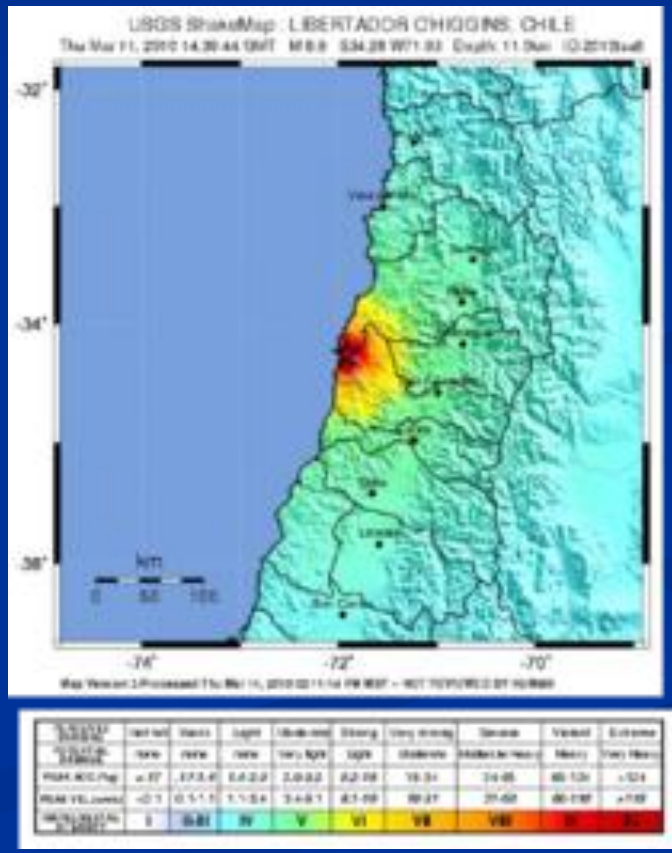
- Expect Lots of Aftershocks
- Crustal Fault Reactivation Possible

Feb 27, 2010 M8.8 Subduction



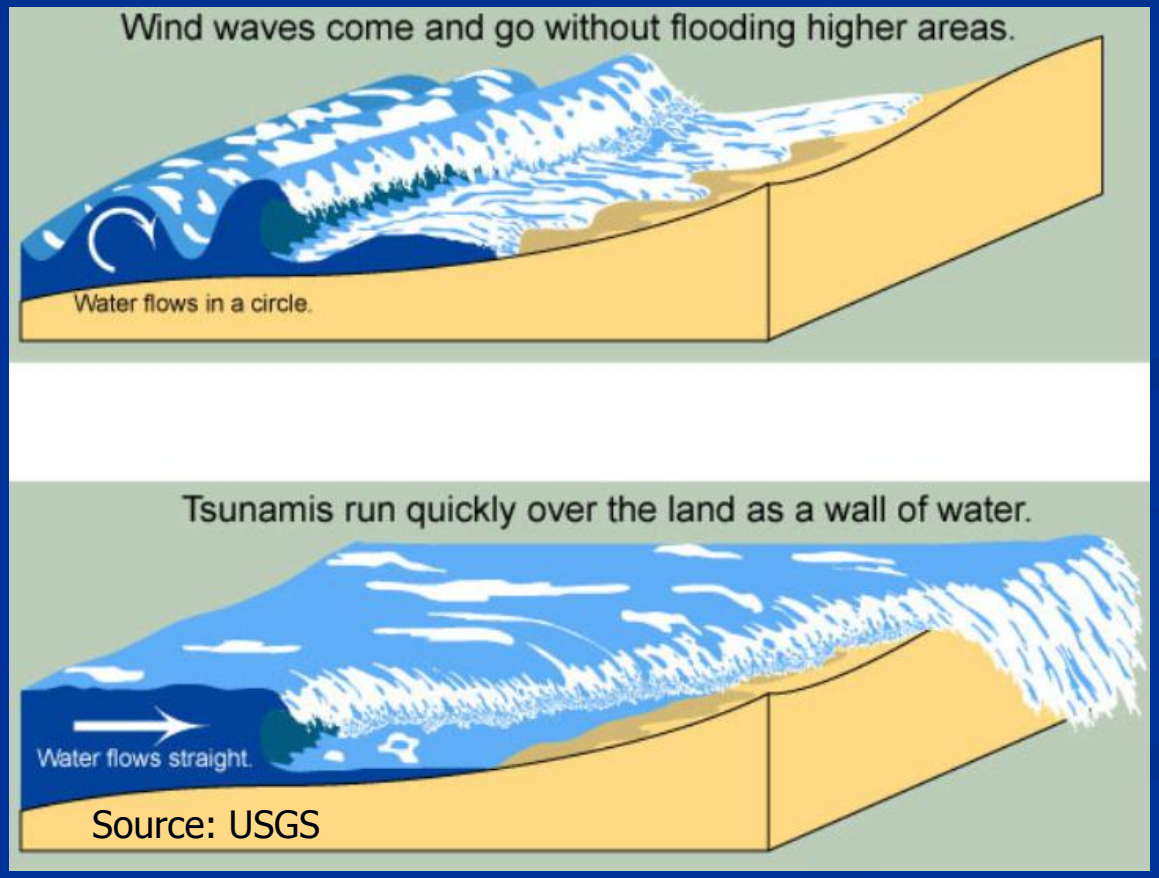
PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<.17	.17-1.4	1.4-3.9	3.9-9.2	9.2-18	18-34	34-65	65-124	>124
PEAK VEL.(cm/s)	<0.1	0.1-1.1	1.1-3.4	3.4-8.1	8.1-16	16-31	31-60	60-116	>116
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

March 11, 2010 M6.9 Crustal



Cascadia: Double Whammy! Earthquake + Tsunami

Tsunami: arrives ~20 minutes
Waves for many hours



Hazards/Effects

- Ground shaking
- Tsunami (coast)
- Coast Subsidence
- Liquefaction
- Lateral spreading
- Landslides
- Ground Settlement
- Seiches (waves)
- Fires
- Hazmat spills
- Infrastructure damage
- Black out, Fuel shortage, etc

Deaths, Dollars & Downtime

Oregon Death Estimates from Cascadia~5,000

- Weak building collapses
  - Unreinforced masonry (URMs)
  - High risk schools (300,000 exposed)
- Tsunami flood zones
  - ~22,000 residents homeless

YWang, DOGAMI, 2013

Deaths, Dollars & Downtime

Japan's Damage
~$300 Billion (US)
~6% GDP

Chile's Damage
$30 Billion (US)
18% GDP

Oregon Estimates
>$32 Billion

Washington Estimates
~$49 billion

Oregon Estimates
> 35,000 Buildings Destroyed
> 250,000 Buildings Damaged

Deaths, Dollars & Downtime

Source: Port of Portland

- Tsunami zone: prolonged recovery
- Infrastructure services down
- Damage to water, energy & transportation
  - Water systems, incl. supply/dams
  - Energy (fuel, natural gas, electrical systems)
  - Transportation (highways, rail, airports, ports)

Seismic Risk to Dams: Hazards & Vulnerabilities & Impact

- Fault Rupture (fault created river valleys)
- Ground Shaking (multiple earthquake sources)
- Liquefaction (dams built on alluvium)
- Landslides (dams at landform constrictions)
- Dam Slope Stability

- No "code" requirements (vs building codes)
- Selected Leaders & Regulators: FEMA, FERC, USBR, USACE, state dam safety officials

Fault Rupture of Ground Surface

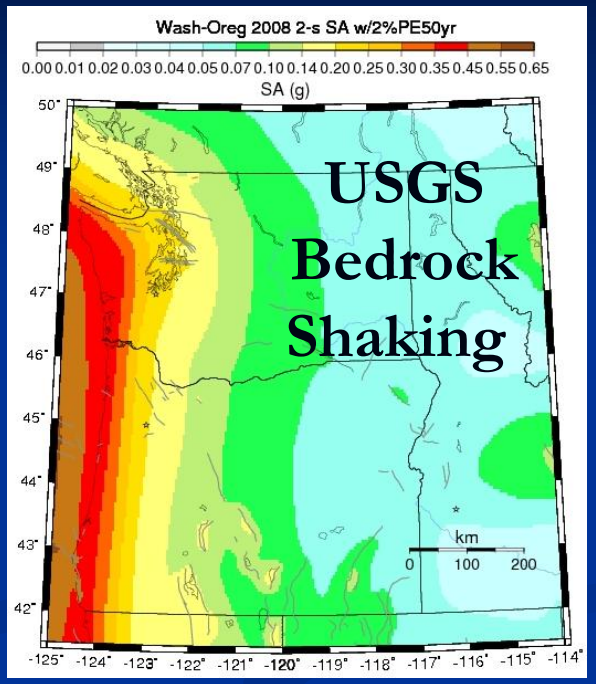
Shikung Dam, 1999 Taiwan M7.6

~8 m displacement fault rupture & 0.5 g

Shaking, incl Local Soil Effects

Local Site Response: Influence of Soils

Amplification of Shaking

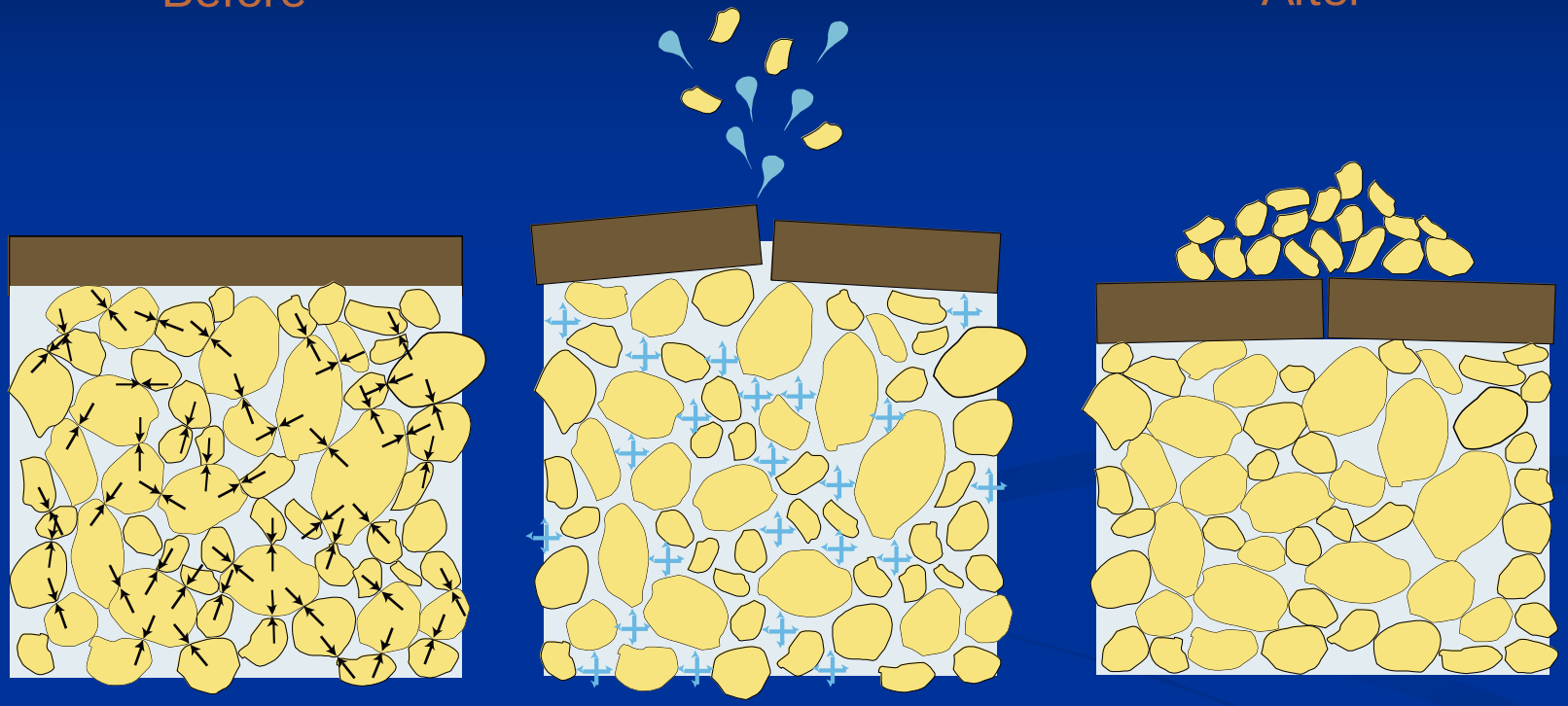


Soil Liquefaction

Before

During Shaking

After



Sand supports loads through grain-to-grain contacts

Fluid pressure rises
Grains float apart
Sand loses strength & can flow downhill
Water, sand ejected

Sand is compacted
Sand volcanoes on surface

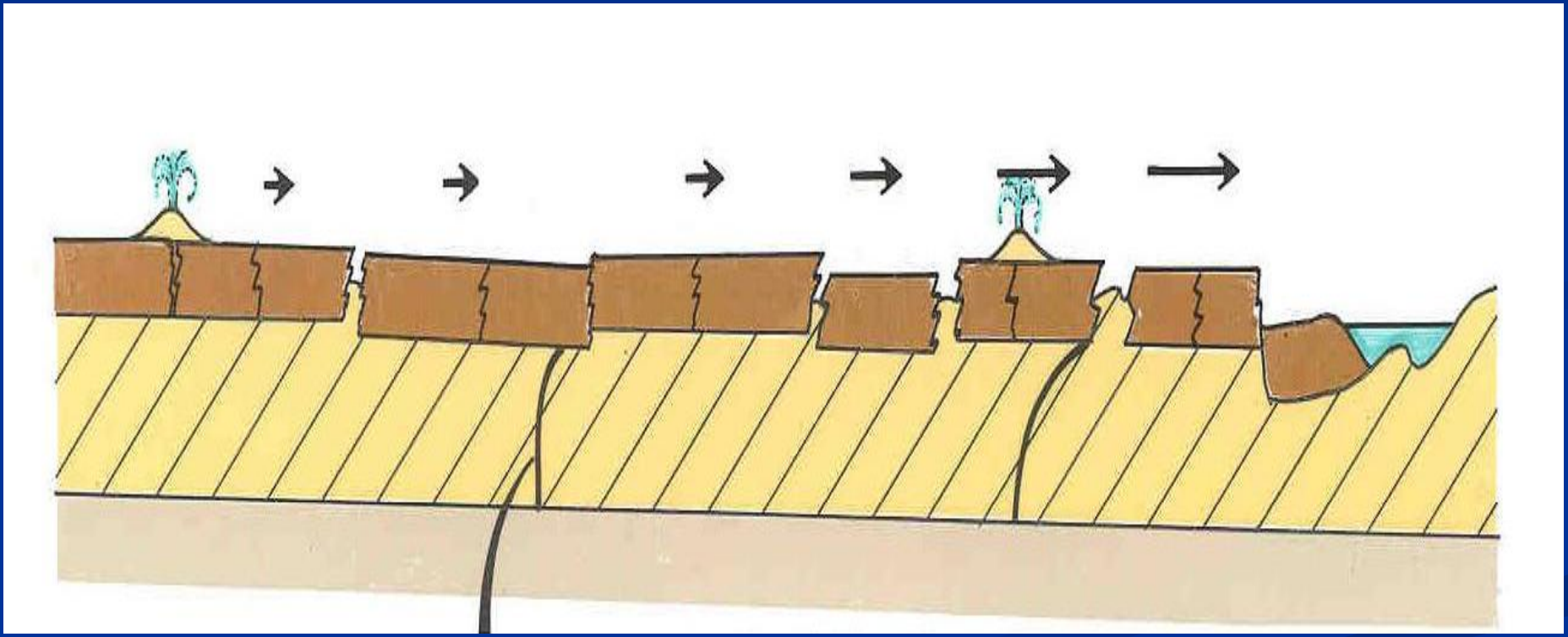
Courtesy: ERoeloffs

Sand boils, Nisqually Wildlife Refuge

Photo: Nisqually Earthquake Clearinghouse

Courtesy: ERoeloffs

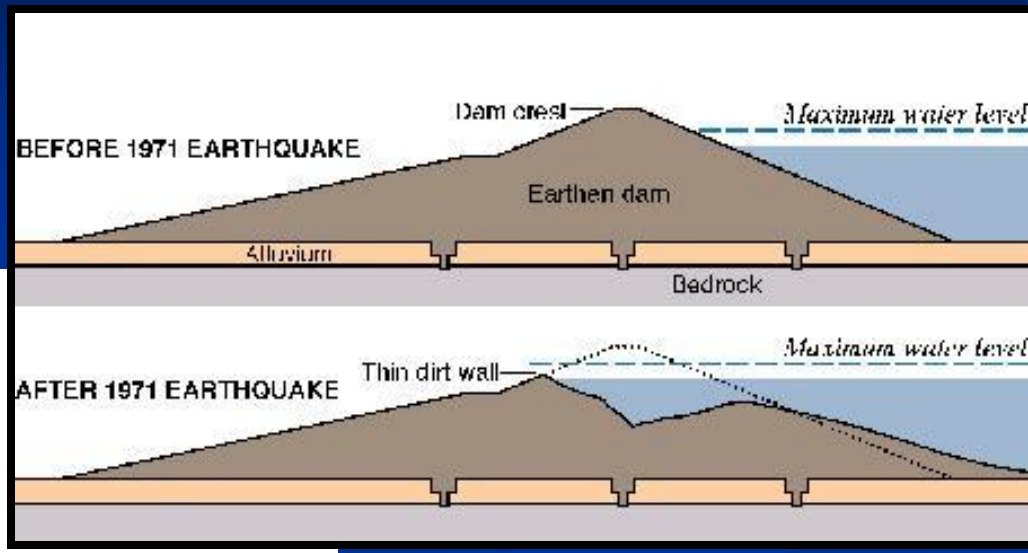
Lateral Spreading
(Permanent Ground Displacement)

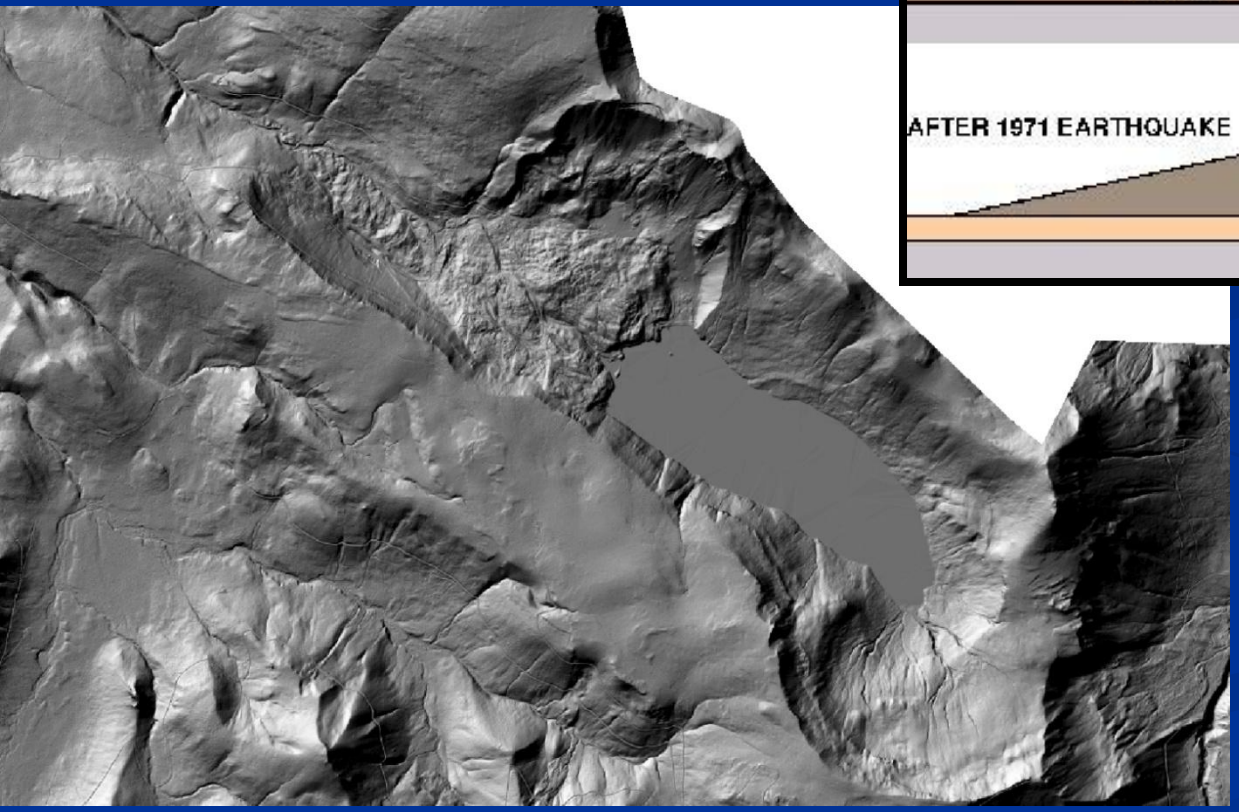


Lateral Spreading in Chile & Japan

Source: ASCE COPRI

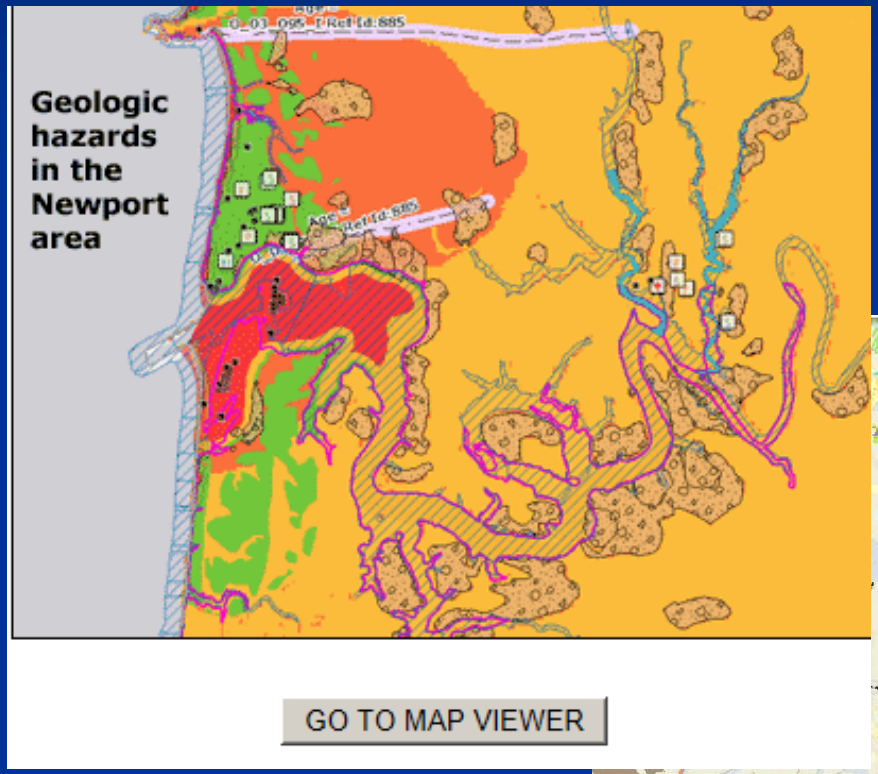
Landslides & Dam Slope Stability

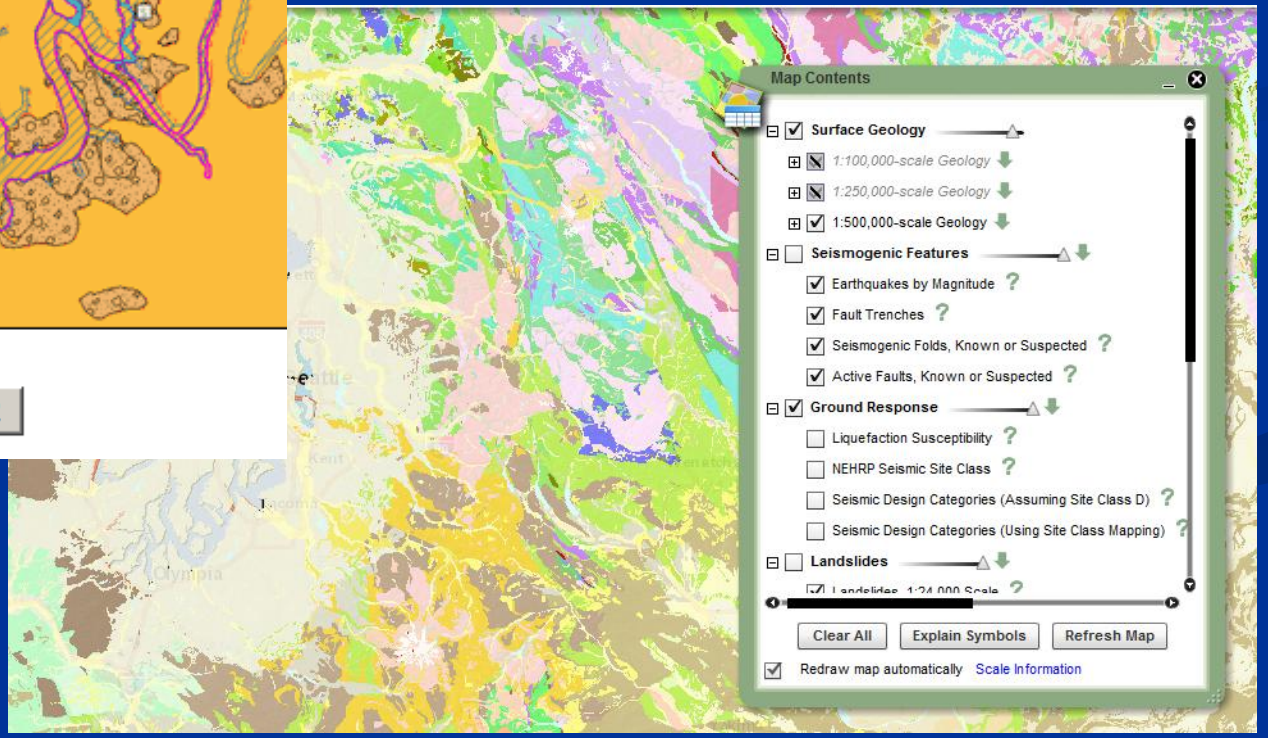




Bull Run Lake, Lidar

OR & WA Geology Agencies: tools for regional seismic hazards





Seismic Failure Modes

Internal Erosion/Piping: Dam

Instability or Erosion: Abutments

Instability or Erosion: Foundation

Global Instability (incl. Rapid Drawdown)

Spillway & Outlet Works

Overtopping: Settlement, Seiche,
(incl. Landslide-Induced Seiche)

Consequences / Impacts

- Life Safety
- Economic
- Lifeline services
- Flood Damage Reduction
- Hydropower
- Environmental

Site-Specific Seismic Analyses

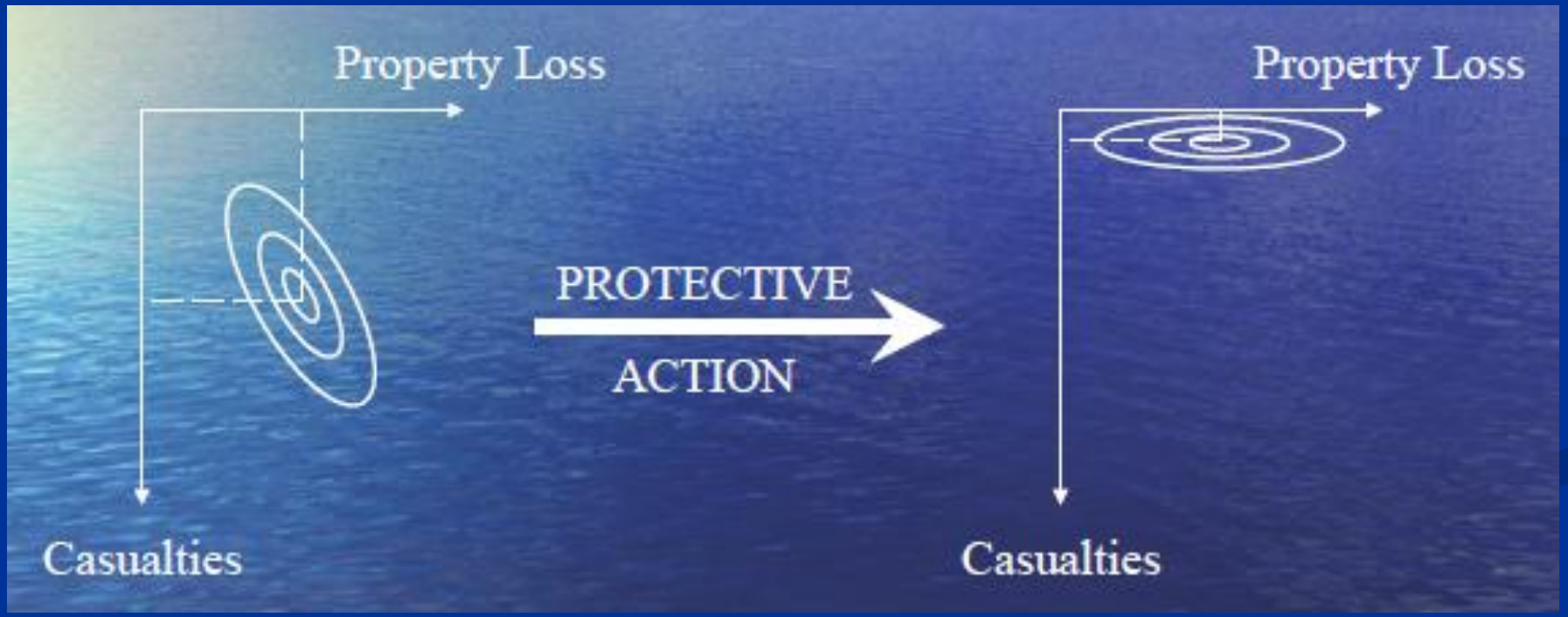
- Determine Seismic Sources
- Determine Design Earthquake Levels
- Evaluate Hazards: liquefaction, landslides, slope stability, settlement, duration effects

Seismic Risk Analyses

- Evaluate each potential failure mode
- Likelihood of failure
- Consequence of failure (impact)
- Consider value of mitigation of each
- Determine benefit-cost ratio of each

Multi-Hazard Risk Analyses

- Hazards (flood, terrorism)
- Consider Mitigation Options & Purposes
  - Is raising dam height to address flooding decreasing slope stability?
  - Warning system: improves life safety, not property



Dam Examples

2008 Wenchuan China M7.9

Damage: 1,803 concrete & embankment dams & reservoirs, & 403 hydropower plants

International Water Power, Sept 2010

Fears for quake-damaged dams

Monday's quake in China damaged hundreds of dams. The 500-foot-high Zipingpu Dam on the Min River upstream of the city of Dujiang-yan suffered "extremely dangerous" cracks, the official Xinhua News Agency reported. A collapse could endanger the Dujiangyan irrigation and flood-control system, an engineering masterpiece downriver that has been in use for more than 2,000 years.

Sources: ESRI, USGS, NGA MSNBC

YWang, DOGAMI, 2013

Japan

<10 m high embankments
"frequently damaged"
by major earthquakes

1964 Niigata M7.5:
146 reservoir embankments
damaged; 7 completely failed

2011: 1 day after
252 dams inspected
7 damage

www.geerassociation.org

745 reservoirs in
Fukushima Prefecture damage

https://www.jstage.jst.go.jp/article/hrl/5/0/5_0_69/_pdf

Nishigo Dam,
longitudinal cracks on
dam crest (2011)

https://www.jstage.jst.go.jp/article/hrl/5/0/5_0_69/_pdf

2011 Japan M9.0

GEER Quick Report 5
www.geerassociation.org

1949 Fujinuma Dam
H=61 ft
Breached; 8 killed

https://www.jstage.jst.go.jp/article/hrl/5/0/5_0_69/_pdf

Fujinuma Dam

Looking upstream

D/S to right side

GEER Quick Report 5
www.geerassociation.org

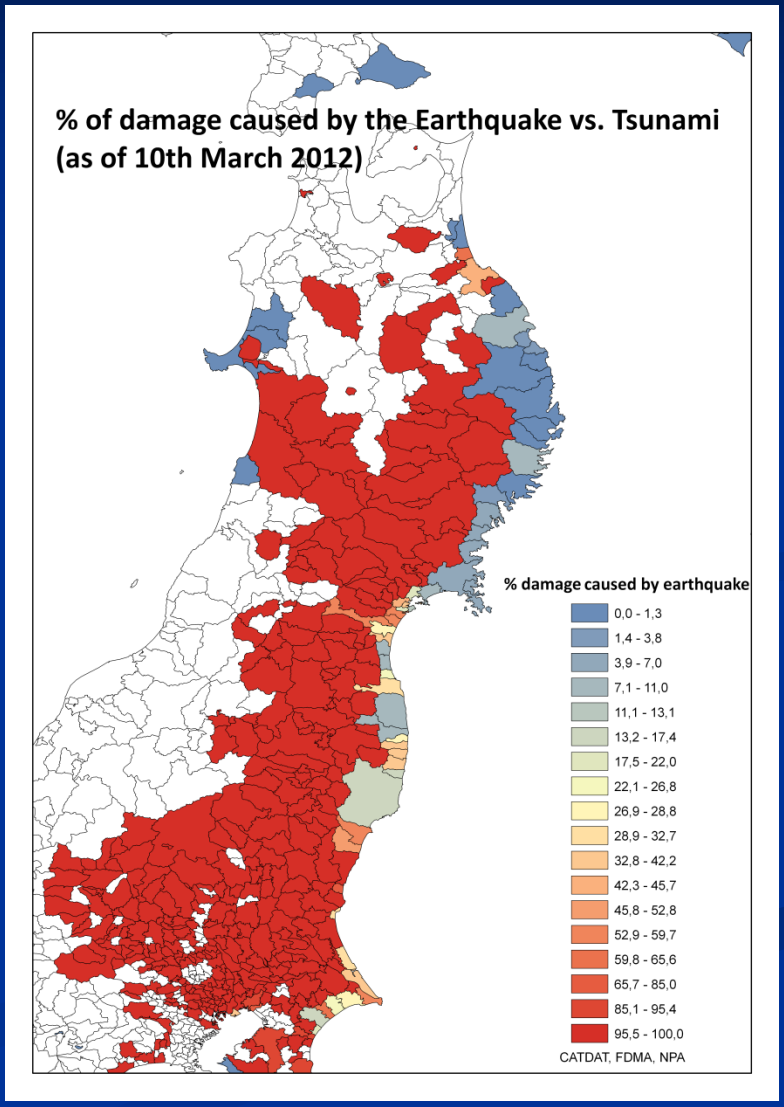
Fujinuma Auxiliary Dam

GEER Quick Report 5
www.geerassociation.org

2011 Japan M9.0

~ 95% deaths from tsunami

~ 40% damage from earthquake
~ 40% damage from tsunami
~ 20% nuclear



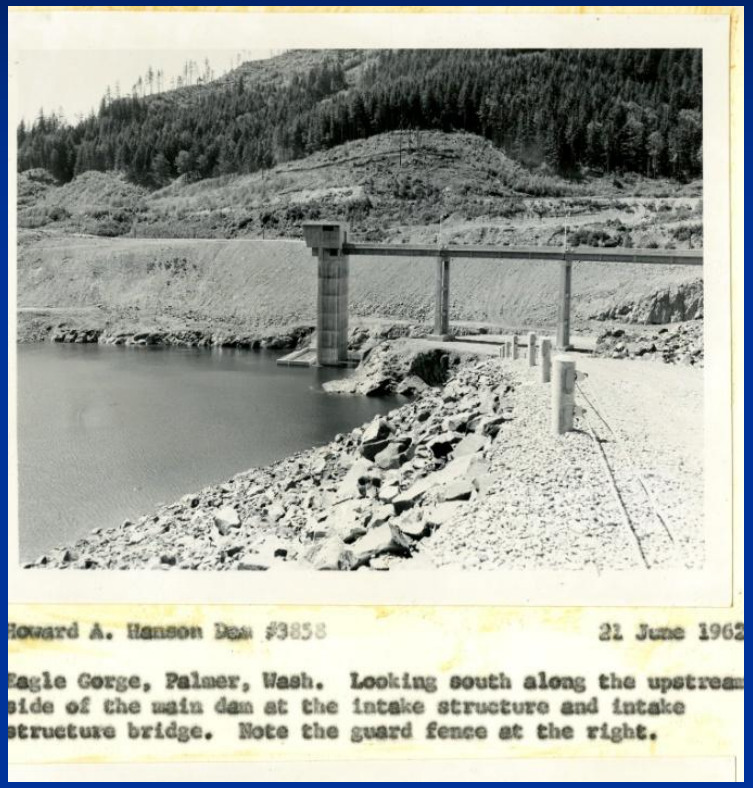
http://quakesos.sosearthquakesvz.netdna-cdn.com/wp-content/uploads/2012/03/Percent-damage-by-earthquake.png

Who is Mitigating?
CA Dams: Decades of Seismic Efforts

Echo Lake Dam, RCC

Lyons Dam, Arch

US ACE Howard Hanson, WA



Source: Richard Smith, US ACE

USBR Scoggins Dam, OR

Risk Analysis: Probability is ~1 in 500 significant deformation (PGA = 0.38 g)

Analyses Source: USBR, D. Levish, 2013

Photo: http://www.usbr.gov/projects/Facility.jsp?fac_Name=Scoggins+Dam

US ACE: 1953 Lookout Pt Dam, OR

embankment & concrete spillway H = 250 ft

Multiple OR Dam Failure "Scenario"

All designed to 0.1 g

1962 Hills Creek Dam 314 ft

1953 Lookout Point Dam 276 ft

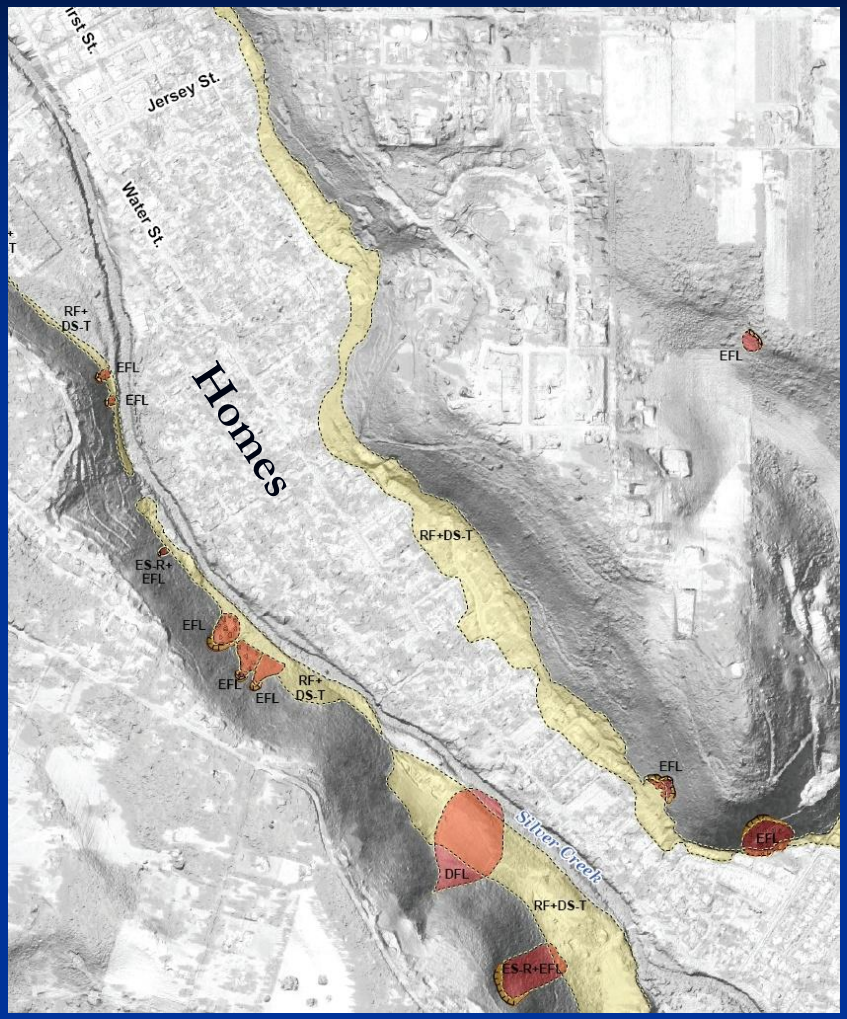
1955 Dexter Dam 117 ft

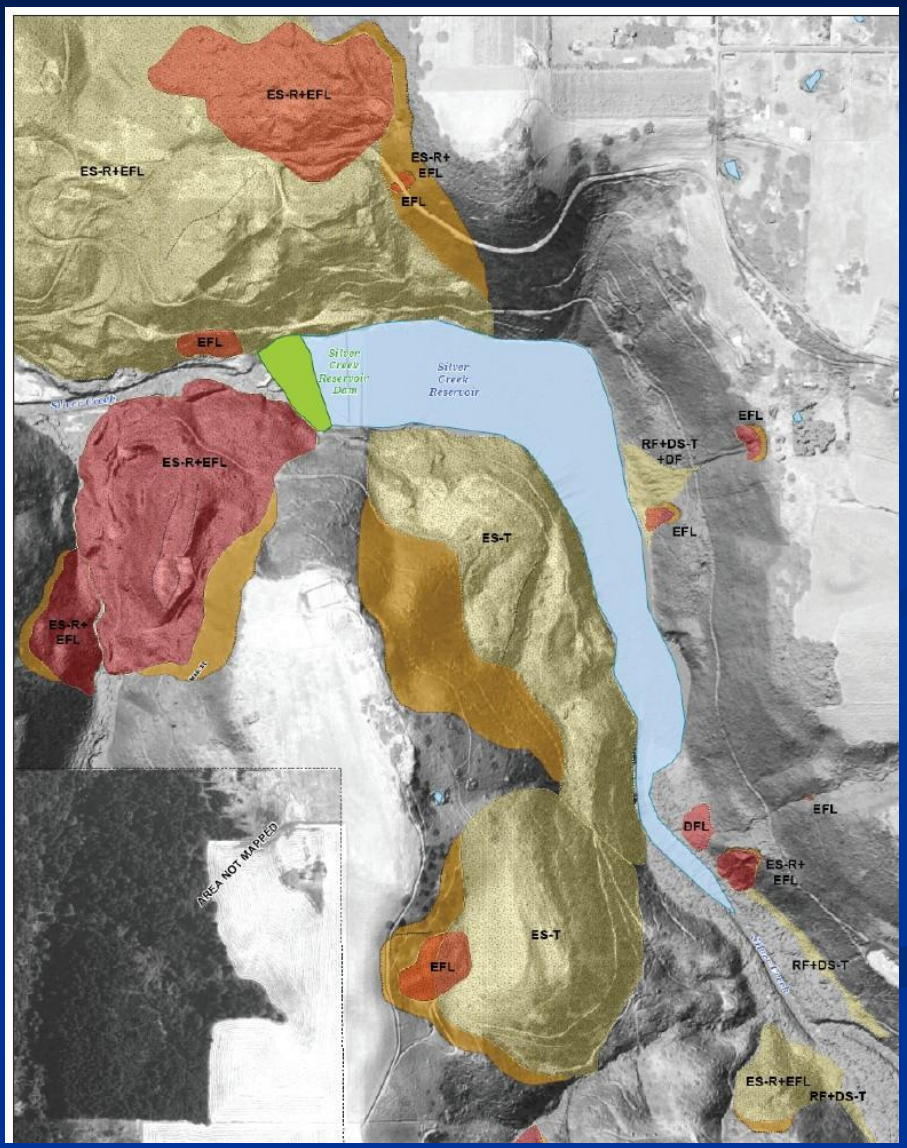
Evacuation of ~250,000 people

~$20 B Losses

Source: OEM, 1987 dam report
(& Eugene/Springfield NHMP, 2009)

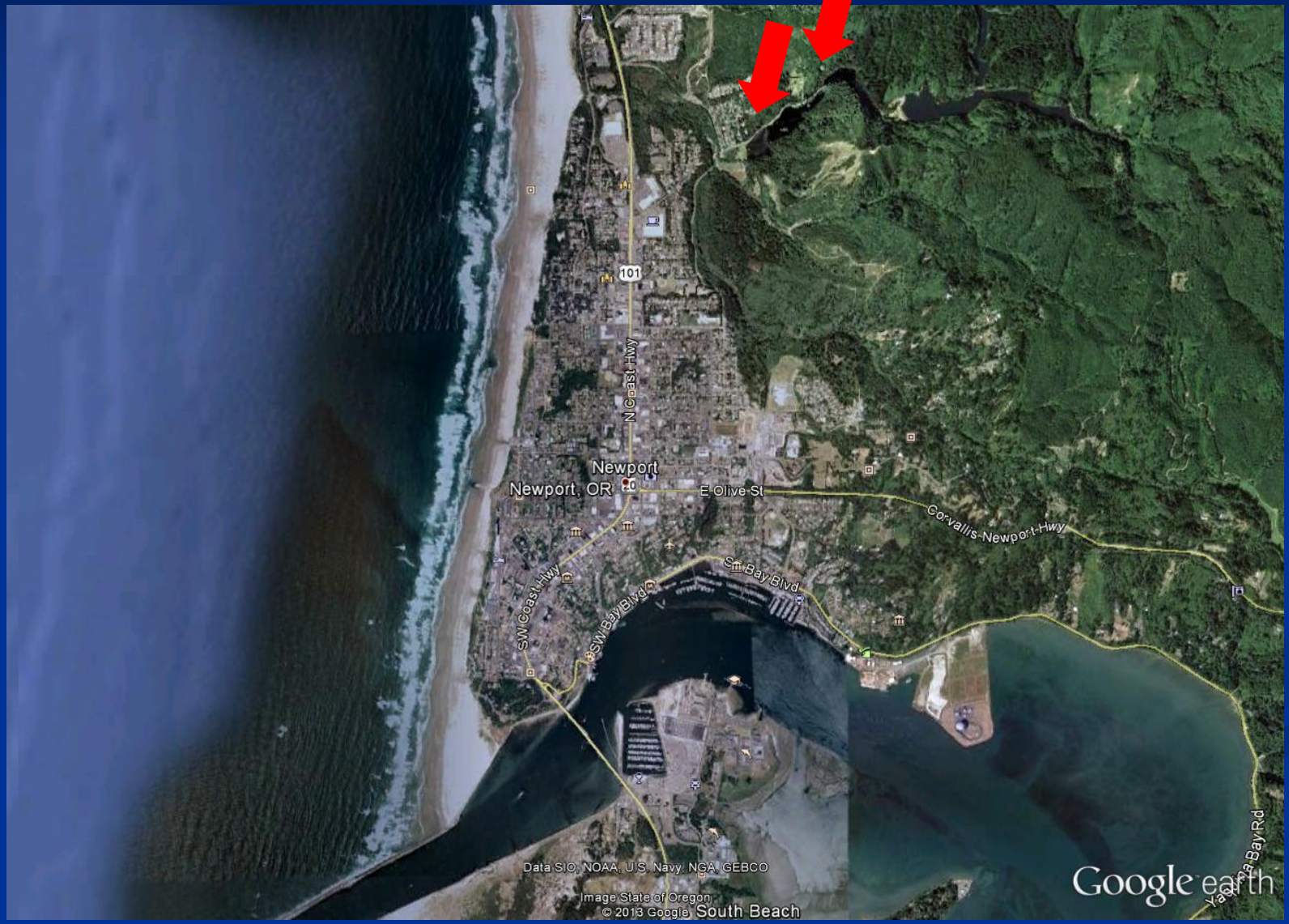
Silverton Dam & Landslides



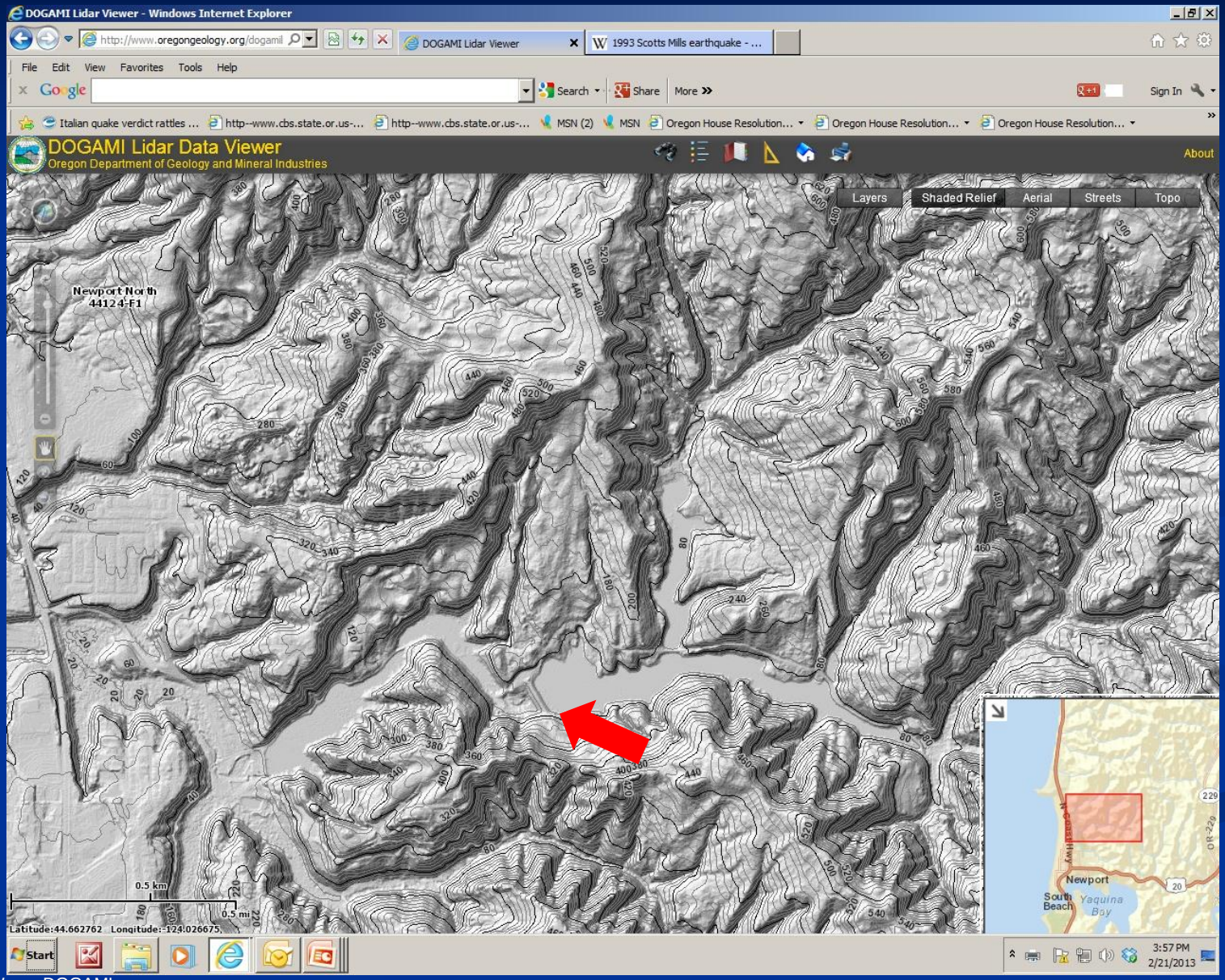


DOGAMI OFR O-12-05

Big Creek, Newport



DOGAMI Lidar Web Viewer



Summary Remarks

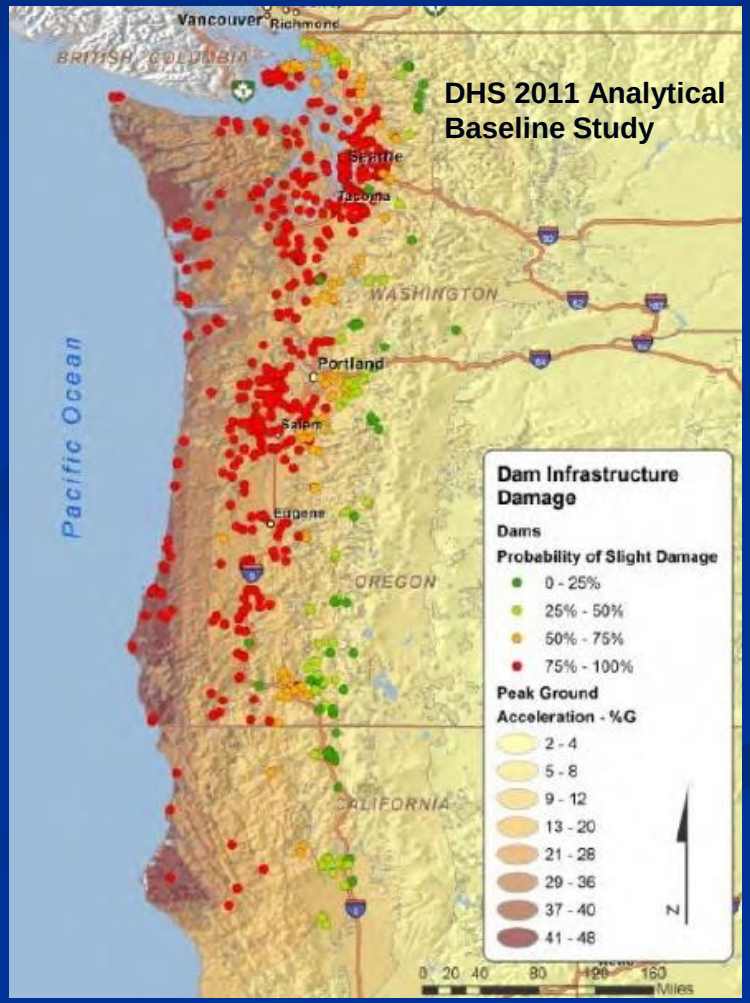
Dam Things to Consider…

- Life safety & property
- Interdependencies: stable water source & electricity
- Seismic analyses of critical dams
- Model shaking duration for potential ground displacement
- Consider multiple hazards & risk

PNW has high risk seismic problem, & Need to build resilience

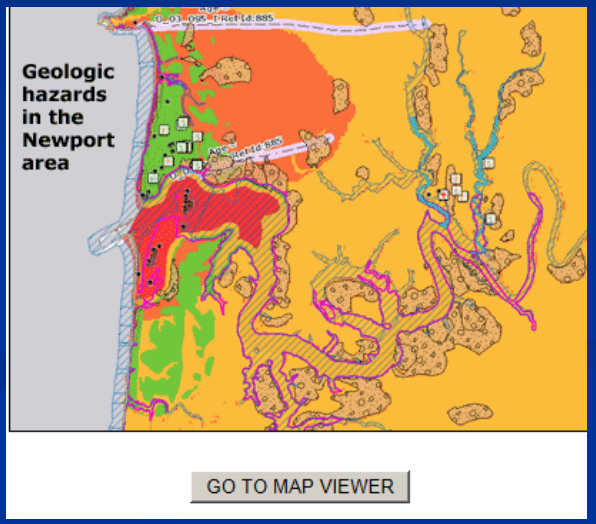
Conduct PNW Dam Risk Study ?

…to better understand, prioritize, plan & mitigate



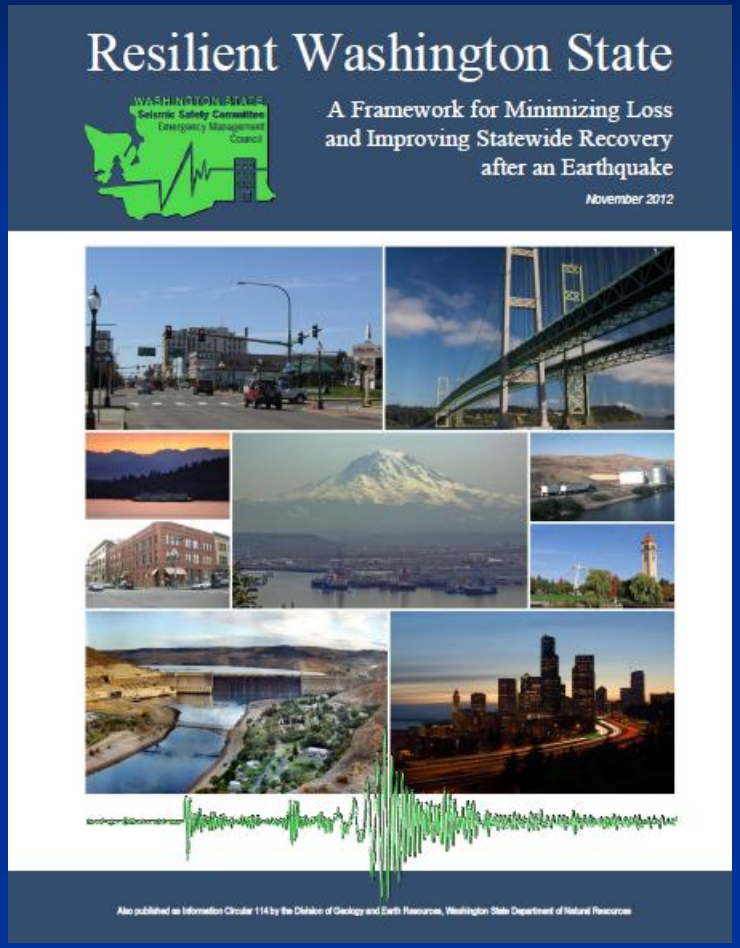
Available Resources

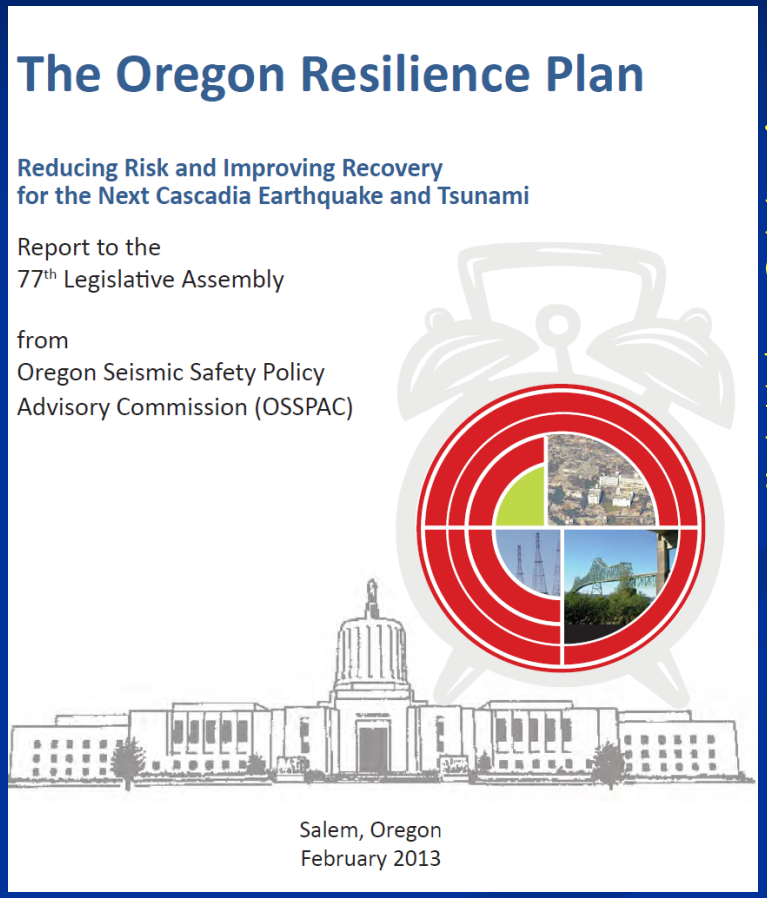
- DOGAMI Geohazard Info www.oregongeology.org
  - GeoHazards Viewer (HazVu)
  - Lidar maps (topography)



• **WA DNR Geologic Survey**
https://fortress.wa.gov/dnr/geology
• **USGS** develop ground motions:
http://earthquake.usgs.gov/hazards/designmaps
• **USBR**: http://www.usbr.gov/ssle/damsafety/Risk/methodology.html
• **FERC** part 12:
http://www.ferc.gov/industries/hydropower/safety/guidelines/part12-regs.pdf

OR & WA
Cascadia Earthquake Resilience Plans





50-Yr Vision

Infrastructure Gap Analyses

Policy Recommend-ations

http://www.dnr.wa.gov/Publications/ger_ic114_resilient_washington_state.pdf

http://www.oregon.gov/OMD/OEM/osspac/docs/Oregon_Resilience_Plan_Final.pdf

Building for Hazards in PNW

Cascadia Fault (bigger hazard than wolf)